Position Control of a Quadrotor under External Constant Disturbance

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Abstract— **In the present work, an adaptive backstepping algorithm is developed in order to counteract the effects of disturbances. These disturbances are modeled as a constant force in the translational model part and as a constant torque in the orientation model part. We make the deduction of the mathematical expression for the proposed control algorithm and also we show its performance in simulation. Additionally, we include some experiments for validating the results obtained via simulation.**

I. Introduction

The UAVs are in a progressive development and by consequence the methods for controlling them are improving. These vehicles can do a wide range of tasks. These tasks may be from domestic use to military missions. These drones are designed to accomplish or achieve specific goals. During the missions, they can undergo some perturbations, such as, a lateral wind or changes in climatic conditions. This work is focused on studying the behavior of a quadrotor under constant disturbances and designing the way to compensate them. For obtaining the model of a quadrotor we can choose either the Newton Euler approach, either the Lagrange method or using quaternions. The reader may consult [1]–[3] for more details. Another important subject is the stability of the vehicle. This has been widely covered in the literature, by instance in [4]–[7]. The system can be stable but it may not accomplish the goals. In this case, it is necessary to conceive and to test control algorithm that increase the performance of the physical system. These algorithms are based on several ideas such as backstepping, constraint input, sliding modes among others. Some of these methods are described in [8]–[13]. The aim is to improve the performance and reduce the effect of disturbance. In this respect, disturbance observers have been designed to apply their respective estimation in order to reduce the impact of these undesired external perturbations. Some examples are shown in [14] and [15]. Other researchers have developed adaptive techniques, see [16], [17]. These algorithms look for reacting in accord to the presented scenario. We are interested in designing one algorithm that reacts face to an unknown constant disturbance. In the next section, it is developed a backstepping method in addition to an adaptive dynamics that rejects sufficiently "slow" perturbations. We use a simplified model of the quadrotor. These perturbations are modeled as an external force in the translational model part and as an external torque in the orientation model part. It is also supposed the attitude control is sufficiently fast to follow the required Euler angles and thrust in order to achieve the reference position.

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II. System Model and Control Algorithm

A. Mathematical Model

We use the approach of Newton Euler for obtaining the model of the quadrotor. The simplified model is

$$\begin{array}{rcl} m\ddot{r} & = & RF + F_g + \bar{k}_u \\ \dot{\eta} & = & B(\eta)\omega \\ \mathbb{J}\dot{\omega} & = & \tau - \omega^{\times}\mathbb{J}\omega + \bar{k}_\tau \end{array} \qquad (1)$$

F means the thrust generated by the helices, F_g is the gravity force and $\bar{k}_u$ is a constant disturbance in the position model part. η stands for the vector of Euler angles, ω is the angular velocity in the body frame. m is the mass of drone and r defines the position of mass center of the drone in the inertial system. R describes the rotation matrix generated in the order yaw-pitch-roll. $B(\eta)$ represents the matrix that relates the angular velocity and the derivative of the Euler angles. $\mathbb{J}$ is the inertia matrix of the drone. $\omega^{\times}$ means the skew symmetric matrix of angular velocity and τ defines the vector of torques applied to the vehicle and $\bar{k}_\tau$ is a constant disturbance in the attitude model part.
This simplified model is used for designing an adaptive control algorithm that let us to counteract the effects of the unknown $\bar{k}_u$ and $\bar{k}_\tau$ by estimating their values. In the following, this algorithm is explained in detail.

B. Position Control Algorithm

The design of the algorithm is divided in two stages, the first one consists in designing the algorithm for position controller and the second one consists in designing the orientation control. We suppose that the orientation algorithm is enough fast so that the position of UAV converges to the desired position. Let us define the position error:

$$e_r = r - r_{ref} \quad \Longrightarrow \quad \dot{e}_r = \dot{r} - \dot{r}_{ref} = v - \dot{r}_{ref} \qquad (2)$$

with r_{ref} as the desired position and $< * , * >$ stands for the inner vectorial product. Now, let us propose a positive definite function to design a convenient velocity v_d that ensures the convergence to the desired position.

$$V_{Lr} = \frac{1}{2} < e_r, e_r > \quad (3)$$

Therefore,

$$\dot{V}_{Lr} =< e_r, \dot{e}_r > \quad (4)$$

and taking v as

$$v_d = \dot{r}_{ref} - K_r e_r \quad (5)$$

it yields,

$$\dot{V}_{Lr}|_{v=v_d} = - < e_r, K_r e_r > \quad \leq 0 \quad \forall\ t \geq 0 \quad (6)$$

with K_r as a positive diagonal matrix. Then, let us define the velocity error:

$$e_v = v - v_d \quad \Longrightarrow \quad \dot{e}_v = \dot{v} - \dot{v}_d = \frac{1}{m}(u + \bar{k}_u) - \dot{v}_d \quad (7)$$

where $u = RF + F_g$. Let be the positive definite function:

$$V_{Lv} = V_{Lr} + \frac{1}{2} < e_v, e_v > \quad (8)$$

and consequently,

$$\dot{V}_{Lv} = \dot{V}_{Lr} + < e_v, \dot{e}_v > \quad (9)$$

Now, taking into account that $v = v_d + e_v$, the expression $\dot{V}_{Lv}$ can be written as:

$$\dot{V}_{Lv} = - < e_r, K_r e_r > + < e_r, e_v > + < e_v, \dot{e}_v > \quad (10)$$

and by choosing u as,

$$u_d = -\hat{k}_u + m\left(\dot{v}_d - e_r - K_v e_v\right) \quad (11)$$

with $\hat{k}_u$ as the estimate of $\bar{k}_u$, it results:

$$\dot{V}_{Lv} = - < e_r, K_r e_r > - < e_v, K_v e_v > + \frac{1}{m} < e_v, \tilde{k}_u > \quad (12)$$

where K_v represents a positive diagonal matrix. Now, let us define the error between the estimate and the unknown disturbance as

$$\tilde{k}_u = \bar{k}_u - \hat{k}_u \quad (13)$$

if $\bar{k}_u$ is constant, thus, we have

$$\dot{\tilde{k}}_u = -\dot{\hat{k}}_u \quad (14)$$

this result will be used in the derivative of the following augmented positive definite function

$$V_{Lv2} = V_{Lv} + \frac{1}{2} < \tilde{k}_u, {\gamma_1}^{-1} \tilde{k}_u > \quad (15)$$

with γ_1 as a positive diagonal matrix. Therefore,

$$\begin{aligned} \dot{V}_{Lv2} \quad = \quad & -K_r < e_r, e_r > -K_v < e_v, e_v > \\ & + \tfrac{1}{m} < e_v, \tilde{k}_u > + < \tilde{k}_u, -{\gamma_1}^{-1} \dot{\hat{k}}_u > \end{aligned} \quad (16)$$

and taking

$$\dot{\hat{k}}_u = \frac{\gamma_1}{m} e_v \quad (17)$$

as the desired dynamics for $\hat{k}_u$. Thus,

$$\begin{aligned} \dot{V}_{Lv2} \quad = \quad & -K_r < e_r, e_r > -K_v < e_v, e_v > \\ & \leq 0 \quad \forall\ t \geq 0 \end{aligned} \quad (18)$$

The matrices K_r, K_v, γ_1 are used for tunning the position control algorithm.

C. Attitude Control Algorithm

There exists a relationship between u and (η, F) in such a way that it is possible to find (η, F) from u. Suppose (η_{ref}, F_{ref}) are te values corresponding to $u = u_d$. The thrust vector F and weight vector F_g are defined as follows:

$$F = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \quad F_g = \begin{pmatrix} 0 \\ 0 \\ -mg \end{pmatrix} \quad (19)$$

where g is the gravity acceleration and considered here as $9.81\ m/s^2$. The rotation matrix R is obtained from Euler angles in the order yaw-pitch-roll and has the following expression:

$$R = \begin{pmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi s\theta c\phi \\ s\psi c\theta & c\psi c\phi + s\psi s\theta s\phi & -c\psi s\phi + s\psi s\theta c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{pmatrix} \quad (20)$$

where $s\cdot$ and $c\cdot$ mean $\cos(\cdot)$ and $\sin(\cdot)$ respectively. The yaw, pitch and roll angles are given by ψ, θ, ϕ respectively. The Euler angles vector and the force vector u are

$$\eta = \begin{pmatrix} \psi \\ \theta \\ \phi \end{pmatrix} \quad u = \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} \quad (21)$$

Then, from (1), (19), (20) and (21) it can be deduced the thrust and the Euler angles needed to generate the virtual control u_d. The ψ_{ref} needed can be chosen arbitrarily or conveniently. θ_{ref}, ϕ_{ref} and f_{ref} have the following expressions:

$$\theta_{ref} = \arctan\left(\frac{u_y s\psi + u_x c\psi}{u_z + mg}\right) \quad (22)$$

$$\phi_{ref} = \arctan\left(c\theta_{ref} \cdot \frac{u_x s\psi - u_y c\psi}{u_z + mg}\right) \quad (23)$$

$$f_{ref} = \frac{u_z + mg}{c\theta_{ref} \cdot c\phi_{ref}} \quad (24)$$

Now, let us define the Euler angles error as:

$$e_\eta = \eta - \eta_{ref} \quad \Longrightarrow \quad \begin{aligned} \dot{e}_\eta \quad &= \quad \dot{\eta} - \dot{\eta}_{ref} \\ &= \quad B(\eta)\omega - \dot{\eta}_{ref} \end{aligned} \quad (25)$$

The matrix $B(\eta)$ has the following form:

$$B = \begin{pmatrix} 0 & s\phi/c\theta & c\phi/c\theta \\ 0 & c\phi & -s\phi \\ 1 & s\phi \cdot tg\theta & c\phi \cdot tg\theta \end{pmatrix} \quad (26)$$

with tg as tan. The matrix $B(\eta)$ is not singular if and only if $\cos(\theta) \neq 0$.
Let us propose the next positive definite function:

$$V_{L\eta} = \frac{1}{2} < e_\eta, e_\eta > \tag{27}$$

and by choosing conveniently the angular velocity ω as

$$\omega = \omega_d = B^{-1} \left(\dot{\eta}_{ref} - K_\eta e_\eta \right) \tag{28}$$

with K_η as a positive diagonal constant matrix, it yields

$$V_{L\eta}|_{\omega=\omega_d} = -K_\eta < e_\eta, e_\eta > \quad \leq 0 \quad \forall\ t \geq 0 \tag{29}$$

Now, let us define the angular velocity error as:

$$e_\omega = \omega - \omega_\eta \quad \Longrightarrow \quad \dot{e}_\omega = \dot{\omega} - \dot{\omega}_\eta \tag{30}$$

and keep in mind that,

$$\omega = \omega_\eta + e_\omega \quad , \quad \dot{\omega} = \mathbb{J}^{-1} \left(\tau - \omega^\times \mathbb{J} \omega + \bar{k}_\tau \right) \tag{31}$$

Now, let us consider the following candidate Lyapunov function

$$V_{L\omega} = V_{L\eta} + \frac{1}{2} < e_\omega, e_\omega > \tag{32}$$

hence,

$$\dot{V}_{L\omega} = \dot{V}_{L\eta} + < e_\omega, \dot{e}_\omega > \tag{33}$$

and using (29) and (31), we have

$$\begin{aligned} \dot{V}_{L\omega} \quad = \quad & - < e_\eta, K_\eta e_\eta > + < e_\eta, B e_\omega > \\ & + < e_\omega, \dot{e}_\omega > \end{aligned} \tag{34}$$

Therfore, by choosing

$$\tau = -\hat{k}_\tau + \omega^\times \mathbb{J} \omega + \mathbb{J} \left(\dot{\omega}_\eta - B^T e_\eta - K_\omega e_\omega \right) \tag{35}$$

with $\hat{k}_\tau$ as the estimate of constant disturbance in attitude model. It yields

$$\begin{aligned} \dot{V}_{L\omega} \quad = \quad & -K_\eta < e_\eta, e_\eta > -K_\omega < e_\omega, e_\omega > \\ & + < e_\omega, \mathbb{J}^{-1} \tilde{k}_\tau > \end{aligned} \tag{36}$$

with $\tilde{k}_\tau$ defined as

$$\tilde{k}_\tau = \bar{k}_\tau - \hat{k}_\tau \tag{37}$$

and we have supposed that $\bar{k}_\tau$ is constant, it results

$$\dot{\tilde{k}}_\tau = -\dot{\hat{k}}_\tau \tag{38}$$

Considering the augmented candidate Lyapunov function:

$$V_{L\omega 2} = V_{L\omega} + \frac{1}{2} < \tilde{k}_\tau, {\gamma_2}^{-1} \tilde{k}_\tau > \tag{39}$$

with ${\gamma_2}^{-1}$ as a positive diagonal matrix. It results

$$\begin{aligned} \dot{V}_{L\omega 2} = \quad & -K_\eta < e_\eta, e_\eta > -K_\omega < e_\omega, e_\omega > \\ & + < \mathbb{J}^{-1} e_\omega, \tilde{k}_\tau > + < \tilde{k}_\tau, -{\gamma_2}^{-1} \dot{\hat{k}}_\tau > \end{aligned} \tag{40}$$

Now, it is taken

$$\dot{\hat{k}}_\tau = \gamma_2 \mathbb{J}^{-1} e_\omega \tag{41}$$

as the desired dynamics for $\hat{k}_\tau$. Therefore,

$$\begin{aligned} \dot{V}_{L\omega 2} \quad = \quad & -K_\eta < e_\eta, e_\eta > -K_\omega < e_\omega, e_\omega > \\ & \leq 0 \quad \forall\ t \geq 0 \end{aligned} \tag{42}$$

The matrices K_η, K_ω and γ_2 are chosen in order to tune the attitude controller.

III. SIMULATIONS

The simulation consists of two tests and they were carried out by means of the software Simulink®. The first one simulates the quadrotor's behavior without the compensation in presence of constant disturbances. The second one considers the behavior of quadrotor but including the compensation of disturbances. The simulation parameters are

$K_r = diag(1, 1, 1)$
$K_v = diag(2, 2, 2)$
$K_\eta = diag(4, 4, 4)$
$K_\omega = diag(8, 8, 8)$
$mass = 0.020\ (Kg)$
$\gamma_1 = diag(1, 1, 1) \cdot 10^{-3}$
$r_{ref} = [1, 1, 1]\ (m)$

$\mathbb{J}_{xx} = 0.00030993\ (kgm2)$
$\mathbb{J}_{yy} = \mathbb{J}_{xx}$
$\mathbb{J}_{zz} = 0.00022103\ (kgm2)$
$\bar{k}_u = [0.25, 0.25, -0.25] \cdot mg$
$\bar{k}_\tau = [-1, 1, 2] \cdot 10^{-3}\ (Nm)$
$\gamma_2 = diag(5, 5, 5) \cdot 10^{-7}$

where mg is the weight of quadrotor. The Fig. 1 shows the behavior of the quadrotor which undergoes two constant vectorial disturbances $\bar{k}_u$ and $\bar{k}_\tau$. We remark in Fig. 1(a) that the system without the adaptive compensation has a position error in steady state while the error with compensation vanishes. Similar remarks can be made about the Euler angles errors. From Fig. 1(c) we deduce that the compensated system uses more energy in order to reduce the error and from Fig. 1(d) we see that torques generated by the drone, instead to converge to zero, they tend to the opposite value of the constant disturbance.

In Figs. 2(a) and 2(b) we observe that disturbance estimates $\hat{k}_u$ and $\hat{k}_\tau$ converge to the applied ones.

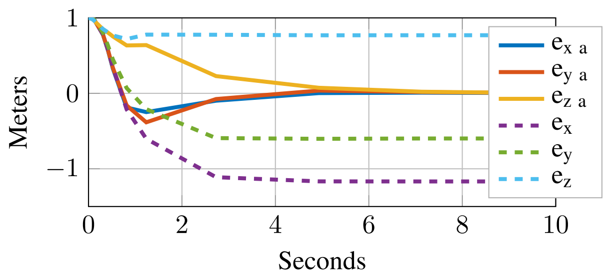
IV. HARDWARE AND EXPERIMENTAL RESULTS

A. Hardware

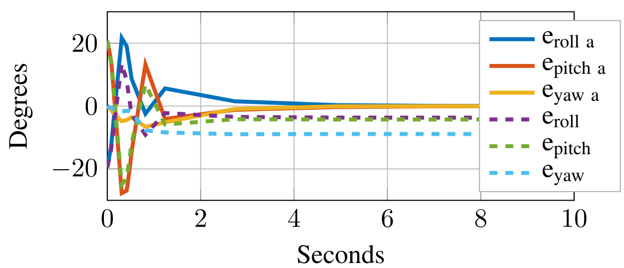
The experiments were developed in the MOCA room at GIPSA-LAB, see [18] for more references. The system of control is showed in Fig. 3. The system uses the Vicon Tracker to get the position and orientation of quadrotor and these data are sent to the PC which computes the position control algorithm. We use the factory internal algorithm of quadrotor for attitude control. The desired Euler angles and the required thrust are sent to the drone as commands via a radio transmitter. The drone used in this experiment is the Blade NanoQX showed in Fig. 4 and its specifications are described in Table I.

TABLE I
NANOQX PARAMETERS

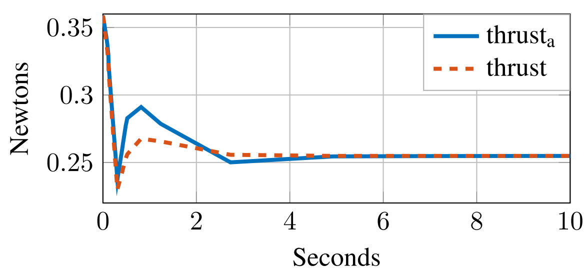
Parameter	Value
mass	0.020 kg
payload	0.006 kg
Transmitter	MLP4DSM
Length	0.140 m
Height	0.030 m
helix diameter	0.05 m
Battery	150mAh 1S 3.7V 25C Li-Po
Motor	6 mm Brushed



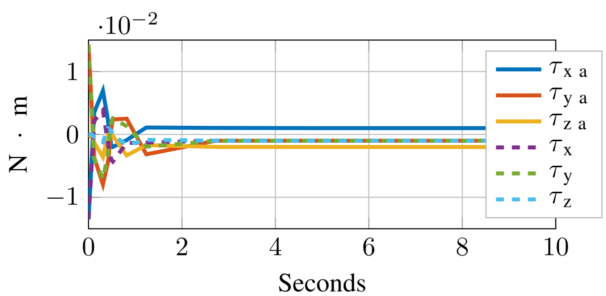
(a) Position Error



(b) Attitude Error



(c) Thrust

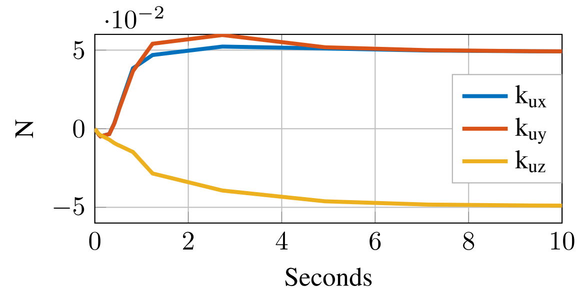


(d) Torques

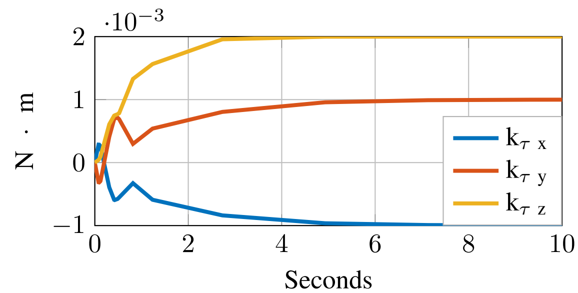
Fig. 1. Simulation of quadrotor under constant disturbances with and without compensation. Subscript "a" stands for "adaptive".

B. Experiments Results

The experiment consists in the implementation of the control algorithm developed before. This experiment is divided in four tests. The first one consists in the position control of the UAV without compensation. The second one takes into account the compensation dynamics. The results are shown in Fig. 5. Fig. 5(a) shows that the quadrotor has a better behavior when the adaptable compensation is present. The disturbance estimate in this case are about zero as shown in Fig. 6.



(a) Estimate of $\bar{k}_u$



(b) Estimate of $\bar{k}_\tau$

Fig. 2. Estimates of constant disturbances $\bar{k}_u$ and $\bar{k}_\tau$

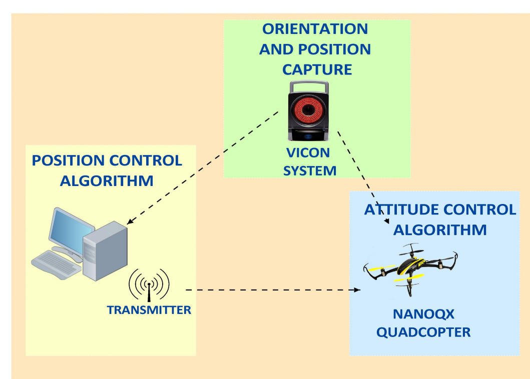


Fig. 3. Control System

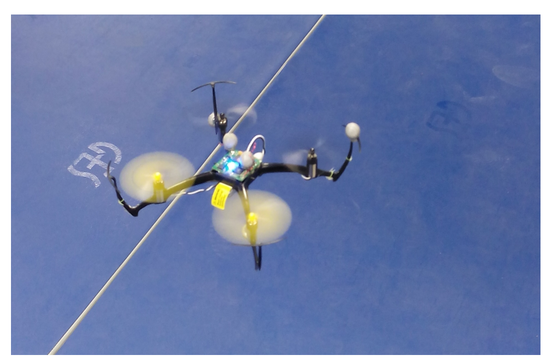
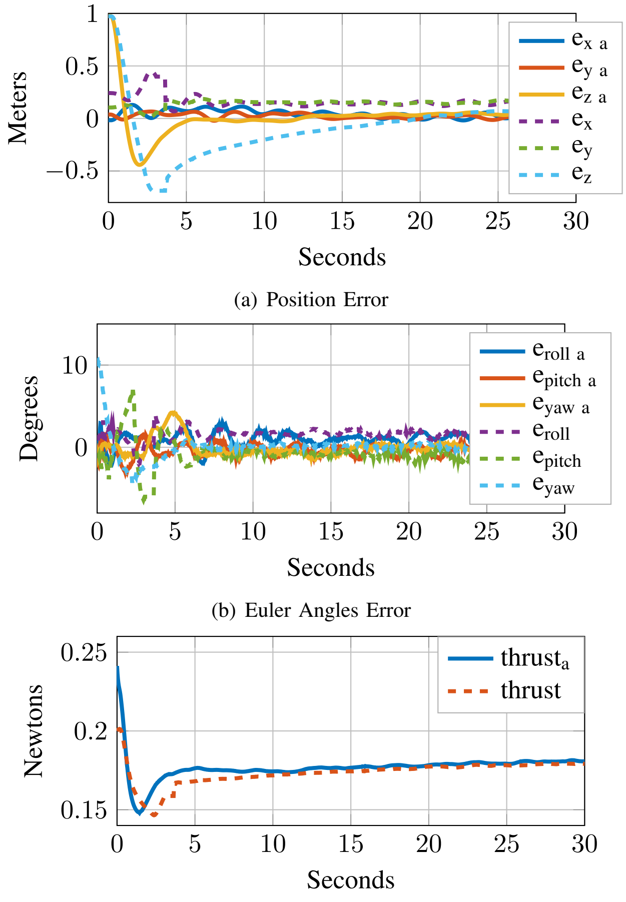


Fig. 4. Quadcopter Blade NanoQX



(a) Position Error

(b) Euler Angles Error

(c) Thrust

Fig. 5. Position Control with and without compensation

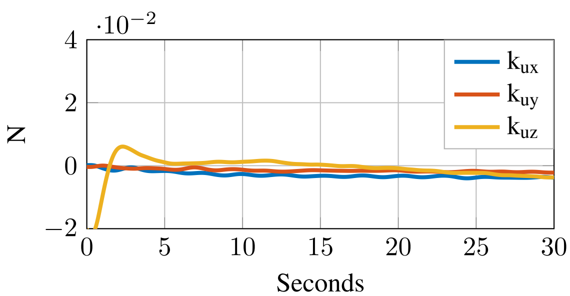
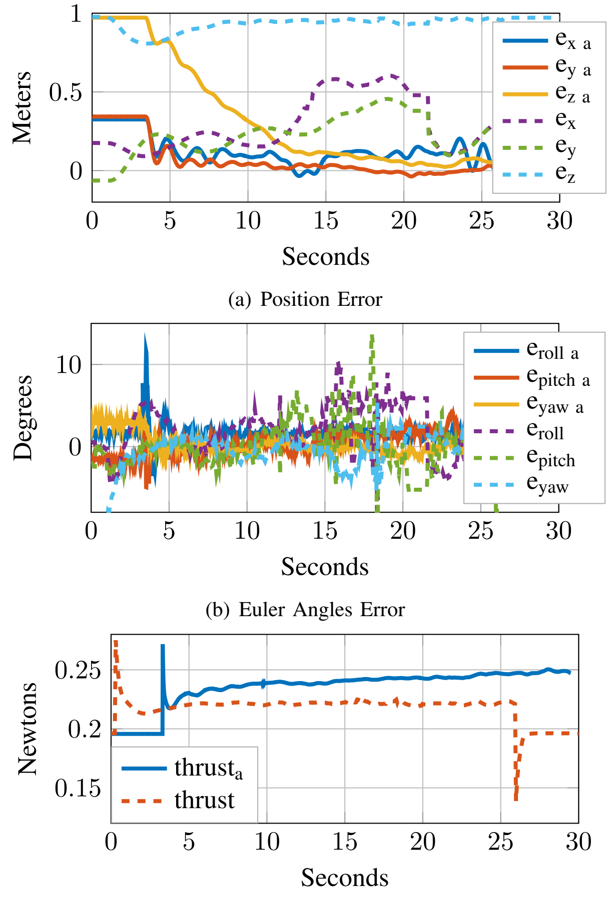


Fig. 6. Estimate $\hat{k}_u$ when UAV has no addtional load

In the next two scenarios we added a load of 4.7 grams, which is about 25 % of vehicle weight. The third one considers the behavior of drone but without compensation while the forth one includes it. The results of these tests are described in Fig. 7. The position error in Fig. 7(a) agrees with the simulations results in Fig. 1(a), especially in e_z. In general, the drone without compensation does not well manage the presence of a disturbance. The quadrotor stayed at a low altitude during the test and was not capable to achieve the reference position. When the control algorithm includes the disturbance estimate, the vehicle has a better performance. Fig. 7(a) shows that error tends to zero and consequently the thrust required is greater as shown in Fig. 7(c). The load estimate is shown in Fig. 8. Particularly, $\hat{k}_{uz}$ agrees with the weight added.



(a) Position Error

(b) Euler Angles Error

(c) Thrust

Fig. 7. Position Control with and without compensation when load added

V. Conclusions

It was developed an algorithm which compensated the applied constant disturbances. This disturbances were modeled as unknown constant forces and torques. The simulation of system showed satisfactory results and these ones were confirmed by means of experiments developed in the MOCA room at GIPSA LAB. The algorithm could estimate the load added to quadrotor. Additionally to identification of load, the algorithm can compensate "slow" unknown dynamics affecting the vehicle behavior and helping by this way to improve its performance.

In future works, this technique will be applied to a bigger drone and also the implementation the torque compensation will be carried out.

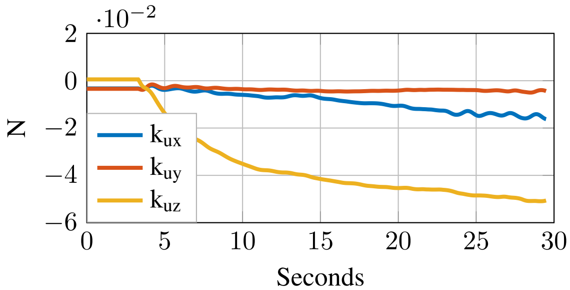


Fig. 8. Estimate $\hat{k}_u$ when UAV has no addtional load

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